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ROYAL AEROSPACE ESTABLISHMENT

PRELIMINARY EXPERIENCE WITH HIGH RESPONSE PRESSURE MEASUREMENTS IN A MULTISTAGE, HIGH SPEED COMPRESSOR

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M. A. Cherrett
J. D. Bryce

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Procurement Executive, Ministry of Defence
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SUMMARY

The investigation of unsteady aerodynamic phenomena within high speed axial turbomachines necessitates the use of a measuring system with a frequency bandwidth of 100-150 kHz. Preliminary experiments to commission and prove a real-time digital data acquisition system have been carried out at RAE Pyestock and are detailed in this paper. The strategy adopted for data analysis is also described, particularly the facility to lock the data capture process to the rotating frame of the machine to carry out phase-locked analysis on-line.

Miniature high frequency response pressure transducers (of 500 kHz natural frequency) were used to measure the unsteady total and wall-static pressures within a high speed axial core compressor. Successful protection of the transducer diaphragm was achieved using a thin RTV 511 Silastomer rubber coating. This and further practical experience regarding the use of such transducers within this harsh environment is described.

A paper presented to the 9th International Symposium on Measuring Techniques for Transonic and Supersonic Flows in Cascades and Turbomachines - 21-22 March 1988, St Catherines College, Oxford University.

LIST OF CONTENTS

1 INTRODUCTION

Propulsion Department of the Royal Aerospace Establishment, Pyestock, (RAE(P)), is engaged on a programme of research to investigate the unsteady flow mechanisms within the viscous endwall and blade wake regions of high speed axial compressors and fans. This paper outlines the strategy adopted for data capture and analysis and presents practical experience gained from a preliminary series of tests within a high speed, five-stage core compressor rig. The principal aims of this work were to commission and prove a data capture and analysis system, and to gain experience in the performance and reliability of miniature high frequency response pressure transducers within the hostile environment encountered in high speed turbomachinery.

2 THE COMPRESSOR RIG

The rig in which these preliminary tests were carried out is shown in Fig 1. The RAE C147 core compressor was designed to deliver a pressure ratio of 6.5 in five stages and is of direct relevance to future core compressor technology. It is a large-scale machine of approximately 1 m diameter, with large interblade gaps to facilitate inter-stage traversing. The preliminary high-response work reported here was 'piggy-backed' onto a major conventional aerodynamic investigation of the steady-state rig aerodynamics.

The large number of blades per stage and the high rig rotational speed (approximately 6800 rev/min), result in blade passing frequencies of between 8.9 kHz and 12.5 kHz. These values are typical of those found in high speed turbomachinery; this in turn dictates the need for a large frequency bandwidth measuring system. Typically, to resolve the unsteady flow phenomena within such machines a bandwidth of up to 10 times the blade passing frequency is required. Hence a measuring system bandwidth of between 100 kHz and 150 kHz is necessary.

3 THE HIGH RESPONSE TRAVERSE PROBES

In these preliminary tests single sensor total pressure probes were traversed behind the first and third stage rotors. In addition, transducers were mounted in the casing between the first three stages of the machine in order to measure unsteady static pressure.

The head of one of the traverse probes is shown in Fig 2 while it is depicted adjacent to a first stage rotor blade in Fig 3. The transducer is a Kulite type XCQ-062 50 psi absolute transducer of 5.08mm barrel length. A conventional pneumatic total pressure port was mounted adjacent to the transducer.

The natural frequency of the diaphragm was of the order of 500 kHz and was assumed to be reasonably flat over the required 100 kHz bandwidth. Diaphragm protection was achieved with 0.051 to 0.076mm coating of RTV 511 Silastomer rubber. Kulite advise that this degrades transducer frequency response by 10%. This and more conventional screening methods are being investigated separately as part of a series of shock tube tests.

The transducer signals were AC coupled and amplified by 100-fold at the rig using DISA 55D26 signal conditioning units of 150 kHz bandwidth. Signal-to-noise ratios of better than 250 were achieved. The amplified signals were transmitted along 50 m of screened cable to the data acquisition system situated in the facility control room.

4 THE DATA ACQUISITION SYSTEM

The data acquisition strategy adopted is to digitise the unsteady data in real time. At the heart of the system is a 'Multitrap' modular wave form recorder manufactured by Data Laboratories Ltd; its salient features are listed below.

- Nine channels of analogue/digital (A/D) store modules (extendable to 20)
- A/D store capacity of 65536 data samples per channel.
- 12-bit A/D conversion, although this drops to 9-bit resolution at higher sampling rates.
- Simultaneous sampling of all channels at up to 1 MHz.

Sampling at a high data rate is necessary in order to achieve good blade passage resolution. For example, sampling at 1 MHz behind the third stage rotor at design speed, gives a resolution of 82 samples per blade passage.

A schematic view of the data acquisition and analysis system is shown in Fig 4. The acquisition system consists of three main components: the wave form recorder or digitiser, a Hewlett Packard HP310 host micro computer, and a 20 Mbyte Winchester disc for storage. On completion of a data capture event, or events, the data are downloaded from the A/D store modules to the host micro computer where they may be processed 'on-line' before storage on the Winchester disc. Data archived on the disc may be 'post-processed' on the micro computer system after the rig 'run'. Additionally data may be transferred to a VAX 11-780 where increased computing power is required.

The 'on-line' processing is concerned with carrying out 'phase-locked' analysis of the data. This involves locking the data capture process to the rotating frame of reference within the machine. Hence an analysis of the time

dominant periodic and random unsteadiness associated with a number of blade passages over a finite number of rotor revolutions is made[2]. This is shown schematically in Fig 5.

The A/D store modules may be partitioned into as many segments as there are rotor revolutions to be considered. This is a powerful feature of this system. On receipt of the once-per-revolution trigger pulse the recorder is switched on for as long as it takes to sample a predetermined number of blade passages. The data are stored in the first segment of the partitioned memory. On receipt of the second trigger pulse the same passages are sampled. This continues until the segmented memory is full. The data are then downloaded to the micro computer where they are statistically processed into the phase locked average, periodic and random components. From typically 128 segments of raw data only three, containing the phase-locked information, are stored on disc as voltage levels for subsequent conversion to engineering units.

The phase locked parameters are defined briefly as follows:

(a) the phase locked average. This is the sum of the individual 'raw' segments of data meaned over the number of rotor revolutions (or segments recorded), *ie*

$$V(t) = \frac{1}{N} \sum_{K=1}^{N} V_k(t) \quad ,$$

where $V_k(t)$ = raw data trace values,
N = number of rotor revolutions
and $V(t)$ = phase locked average value;

(b) the phase locked periodic 'turbulence' parameter. This is derived directly from the above, and is the square of the phase locked average

$$T_p^2(t) = V(t)^2 \; ;$$

(c) The phase locked random 'turbulence' parameter. This is determined by: comparing each segment of 'raw' data with the phase locked average trace, squaring the difference between the two traces, summing, and meaning over N revolutions.

$$T_r^2(t) = \frac{1}{N} \sum_{K=1}^{N} (V_k(t) - v(t)^2 \quad .$$

A total turbulence parameter $T_t(t)^2$ may be derived by adding $T_p(t)^2$ and $T_r(t)^2$,

$$T_t(t)^2 = T_p(t)^2 + T_r(t)^2 \quad .$$

However, it is noted that if this equation is used $T_p(t)^2$ and $T_r(t)^2$ must be statistically independent if additional terms are to be excluded from the right-hand side of the equation[3,4].

To obtain turbulence values the time averaged mean flow needs to be measured. In this preliminary work time-averaged total pressure was measured during the traverse using the adjacent pitot tube. Ideally the mean flow should be determined directly from the transducer electrical output. To do so, however, requires a ten-fold increase in the accuracy currently obtainable using manufacturers' 'passive' compensation for transducer thermal errors, *ie* changes of sensitivity and zero-offset with temperature. A scheme for the digital real time 'active' compensation for these errors is under consideration for future work.

As only the AC transducer signals were measured for this study the thermal zero shift could be ignored. The change in transducer sensitivity with temperature was allowed for by calibrating the transducers over a range of temperatures. The temperature experienced by the transducer *within* the compressor was determined from conventional instrumentation. This temperature was then used to determine the transducer sensitivity using the calibration matrix. The zero and sensitivity changes with temperature measured during the calibration exercise were within the manufacturer's specification. The changes were generally linear over the 140 K temperature range.

Accurate phase locked analysis is dependent upon precise triggering of the data capture process. In this preliminary work a once-per-revolution trigger pulse was obtained by monitoring the magnetic field associated with the third rotor using an Orbit Controls Ltd 70D-10 series probe. The 'pulse' was provided by an iron-coated rotor blade tip, and is shown in Fig 6. The wave form recorder was set up to trigger at a specific voltage threshold on the negative front edge slope of the pulse. The slope of this part of the pulse was -280 mV/μs. The actual voltage at which the recorder triggered was found to vary marginally which resulted in a positioning error equivalent to only 0.5% of the third stage rotor blade pitch.

5 DIAPHRAGM PROTECTION

A considerable fear, expressed before this work, was the ability of the RTV coating to withstand the harsh environment within the compressor. RTV is particularly attractive as its effect on transducer bandwidth is small compared with more conventional screening methods. In practice the transducers have performed well in this respect. Fig 7 illustrates a transducer diaphragm before and after some 20 hours of traversing within the rig. Particles of up to 0.05 mm diameter have impacted the RTV coating but do not appear to have perforated it.

6 ILLUSTRATION OF DATA ANALYSIS

The strength of the phase-locked analysis approach in identifying the time dominent flow from the complex unsteady flows within high-speed turbomachines is illustrated in the following examples. Fig 8 shows two 'total pressure' traces of 'raw' data measured downstream of the first rotor and covering the passage of approximately 19 rotor blades. The upper trace was captured near the hub at 8% blade height. The lower was captured near the tip at 97% blade height. At the hub the blade passages are clearly defined by the total pressure loss associated with the passing wakes. However inter-blade oscillations at harmonics of the blade passing frequency are also evident. At the tip the situation is far more complex. Here it is hard to distinguish the blade passages, the flow being dominated by tip vortex generated unsteadiness at harmonics of the fundamental blade passing frequency. It is difficult to envisage how data could be utilised in this 'raw' form, its complexity emphasising the need for analysis.

Figs 9 and 10 show the periodic and random turbulence parameters for 8% and 97% blade heights. The data cover 8.7 first rotor blade passages and are processed over 128 revolutions and plotted against time. It can be seen from Fig 9 that the peak periodicity near the hub is associated with the wake passing, as would be expected from considering the 'raw' data. The time dominant inter-blade oscillations should also be noted. Peak 'random turbulence' is again associated with the wake passing.

The same turbulence parameters measured near the blade tip are shown in Fig 10. Here the periodic unsteadiness is seen to be dominated by oscillations at harmonics of the blade passing frequency. The random unsteadiness is seen to be dominant at this blade height. Again peaks associated with the wake suction surface are observed, however the extent of the random unsteadiness in the passage is greater than that at the hub. The total turbulence parameters for both 8% and 97% blade height are shown in Fig 11.

Typically phase locked analysis has been carried out over 128 rotor revolutions. Evidence from this work and elsewhere[2] indicates that the phase-locked parameters do not stabilise over less than 50-80 revolutions, depending on the blade height and the flow region being considered. Phase locking over greater than 128 revolutions is unnecessary; this is demonstrated in Fig 12. The top trace is the first segment of raw data captured at 98% blade height behind the third rotor. Approximately six blade passages are covered by these data. The middle trace shows the phase locked average over 128 rotor revolutions, while the bottom trace shows the average over 256 revolutions. Note that there is little difference between the latter. (The DC offset between the three traces has been added to aid this illustration.)

Despite the obvious merit of phase locked analysis, it has been found necessary to carry out supplementary data analysis. From the data shown in Fig 8 considerable harmonic content is evident, near the tip this becomes dominant. The extent of this activity is not easily discernible from phase locked data. Furthermore data from the embedded stages within the machine contain the effects of up-stream blade rows. This is illustrated in Fig 13 where 'raw' data covering some 25 third rotor passages captured at 43% blade height behind the third rotor are shown. In order to understand the complex influences on the flow it is necessary to carry out frequency domain analysis on un-segmented 'raw' data. The Fast Fourier Transform (FFT) of the data from Fig 13 is shown in Fig 14. The strong upstream rotor influence can be seen clearly. Despite the data being captured behind the third rotor, the effect of the second rotor is stronger. The harmonic content of the data is also evident with up to the fifth harmonic of the third rotor blade passing frequency being significant. The low frequency component (at 1.587 kHz) is noteworthy as it is evidence of a strong aeroelastic influence; the frequency matched that noted from stator-mounted strain gauges.

It is not possible to reveal this complex situation through phase-locked analysis alone. However supplementary analysis necessitates capturing an additional un-segmented data sample at each traverse position. This sample must be of sufficient length to provide good frequency resolution in the FFT analysis. Typically 65536 point data records are analysed 'off-line' giving an FFT resolution of 61 Hz. The time penalty encumbent in capturing both segmented data for the phase-locked analysis, and un-segmented data limits the number of positions at which such data could reasonably be obtained.

7 CONCLUSIONS

(1) RTV coating of transducer diaphragms has proved to be sufficiently robust to withstand the harsh environment within a high speed compressor rig.

(2) A high frequency data acquisition and analysis system has been proven and commissioned. The flexible approach adopted demonstrates considerable savings in analysis time over more conventional tape based systems.

(3) The preliminary work described here has proved extremely valuable in gaining early experience of taking high frequency unsteady flow measurements within a high speed compressor research rig. This will be used in future unsteady aerodynamic investigations of high speed core compressor and fan rigs.

(4) Central to the future programme of work is the need to make quantitative measurements in two and three dimensions. This imposes the following problems which are being addressed:

the provision of a digital 'real time' active compensation system for countering transducer thermal errors;

the need to gain a better understanding of the dynamic response characteristics of high frequency pressure transducers;

the need to develop large-bandwidth, multi-sensor aerodynamic traverse probes calibrated for Mach and Reynolds number effects.

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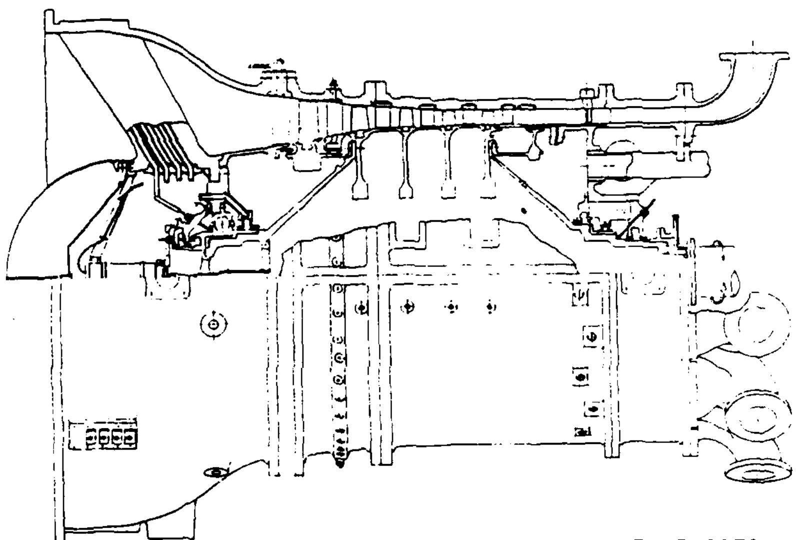
3	R.L. Evans	Turbulence and unsteadiness measurements downstream of a moving blade row. *Journal of Engineering for Power*, pp 131-139, January 1975
4	N.C. Baines	Hot wire and hot film anemometry - private communication - to be published in "Advanced Experimental Techniques in Turbomachinery",PLS-1, D. Japikse (Ed), Concepts ETI Inc., (1988)



DESIGN SPEED BLADE PASSING FREQUENCIES

Rotor 1 = 8900 Hz
Rotor 2 = 10929 Hz
Rotor 3 = 12055 Hz
Rotor 4 = 12506 Hz
Rotor 5 = 10253 Hz

Fig 1 The RAE C147 core compressor rig

Fig 2

Fig 2 Total pressure traverse probe head

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Fig 3 Traverse probe adjacent to a 1st stage rotor blade

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Fig 4

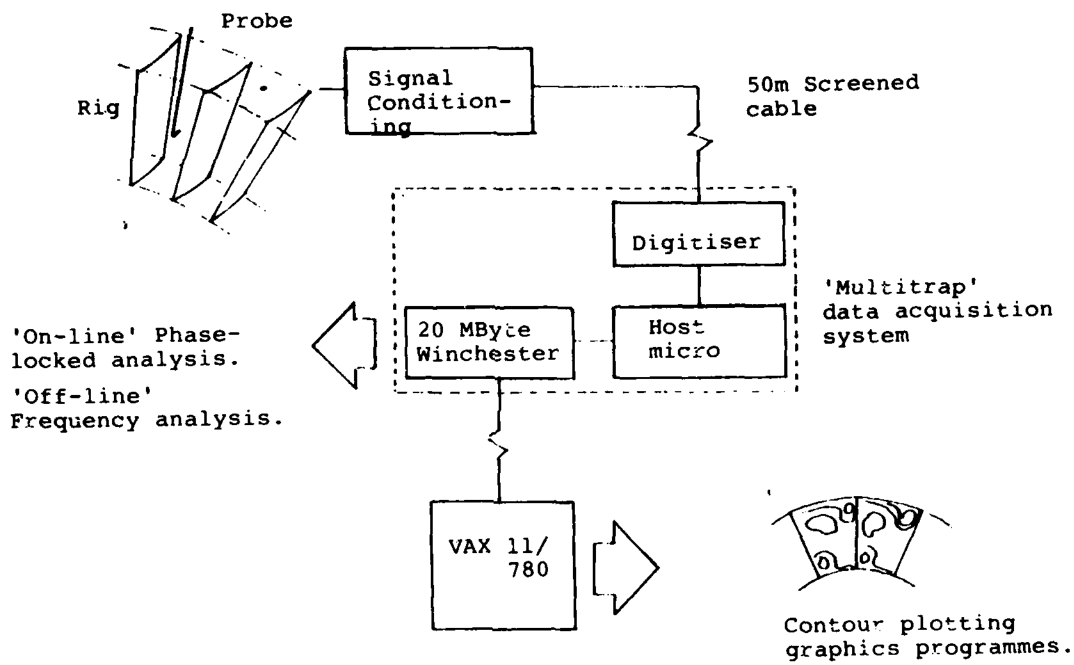

FIGURE 4. THE DATA ACQUISITION AND ANALYSIS SYSTEM

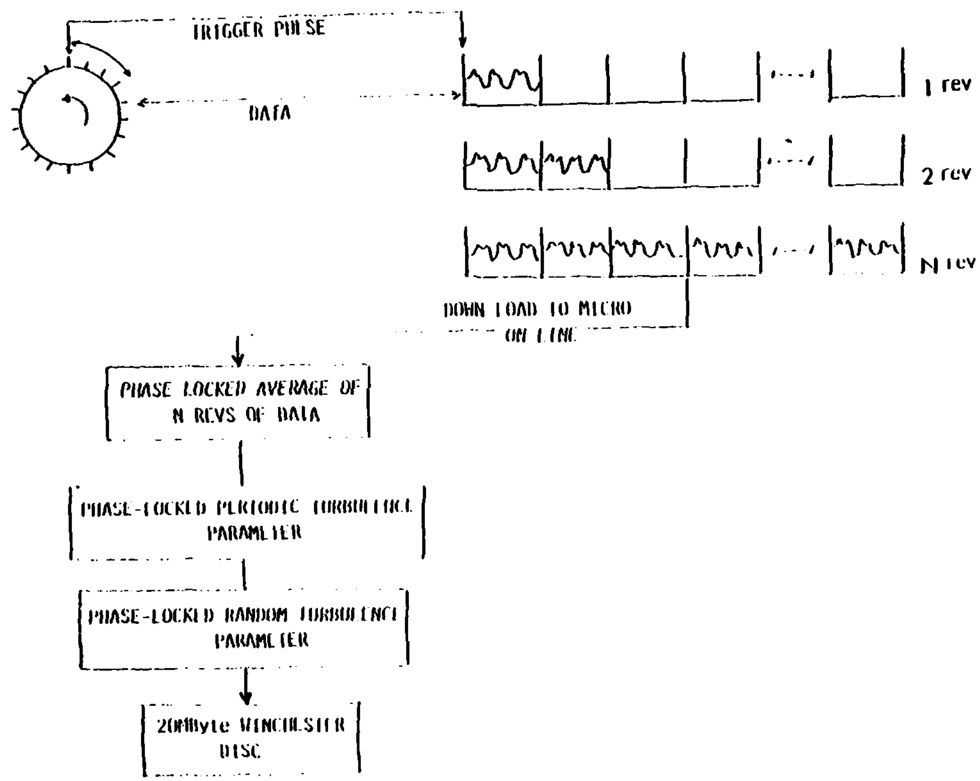

Fig 5 Schematic illustration of the 'on-line' phase-locked processing of data

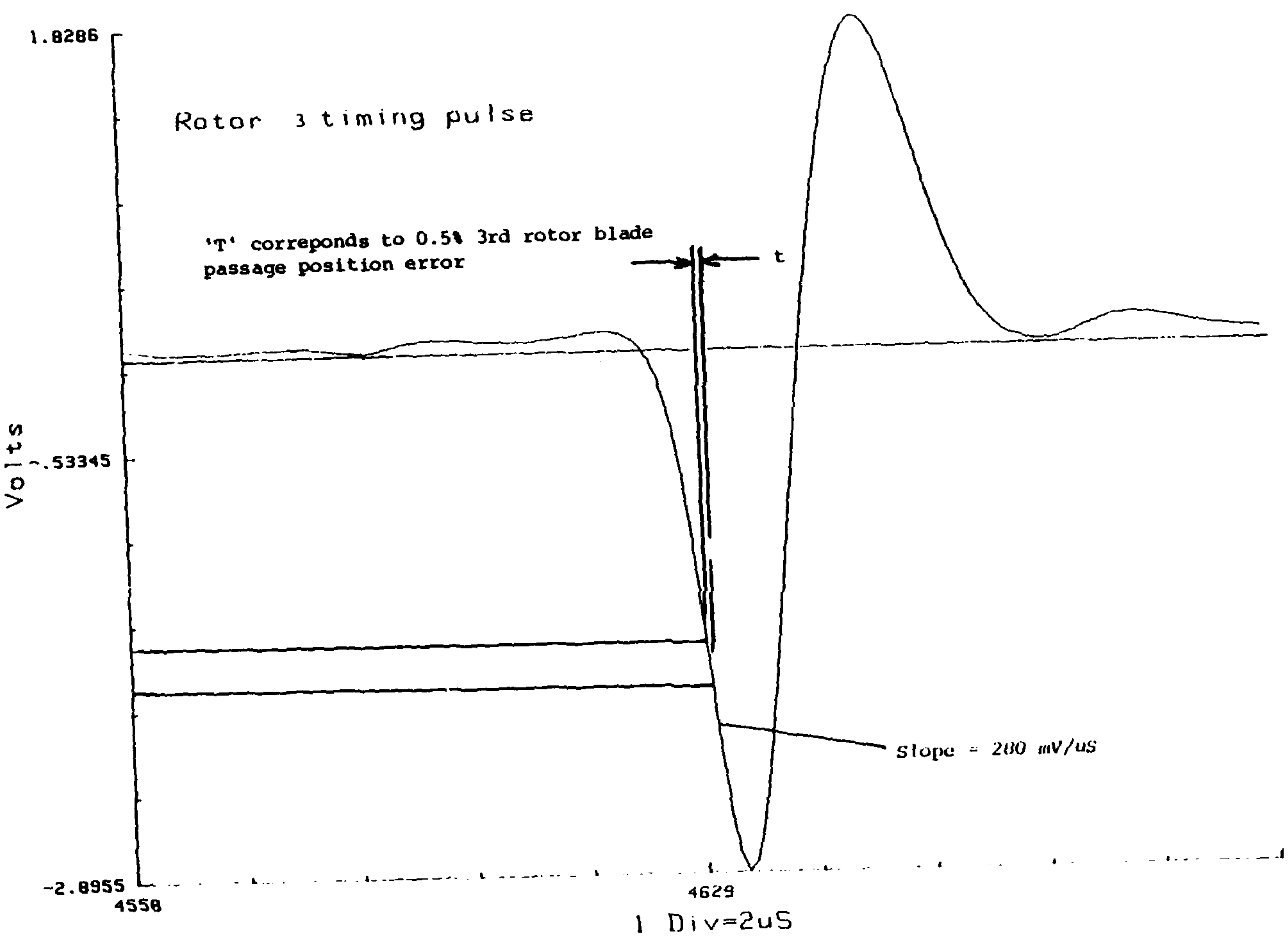

Fig 6 The one-per-revolution timing pulse

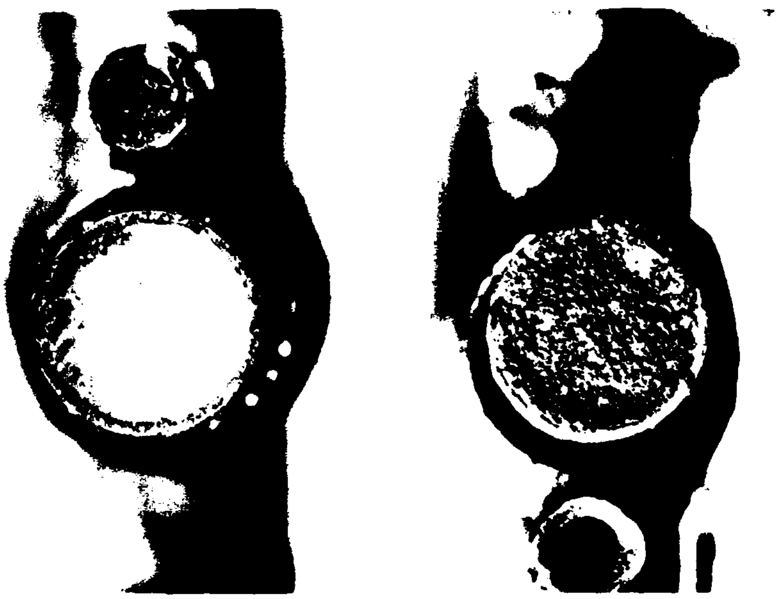

Fig 7 The transducer diaphragm before (left) and after (right) 20 hours of traversing

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Fig 8

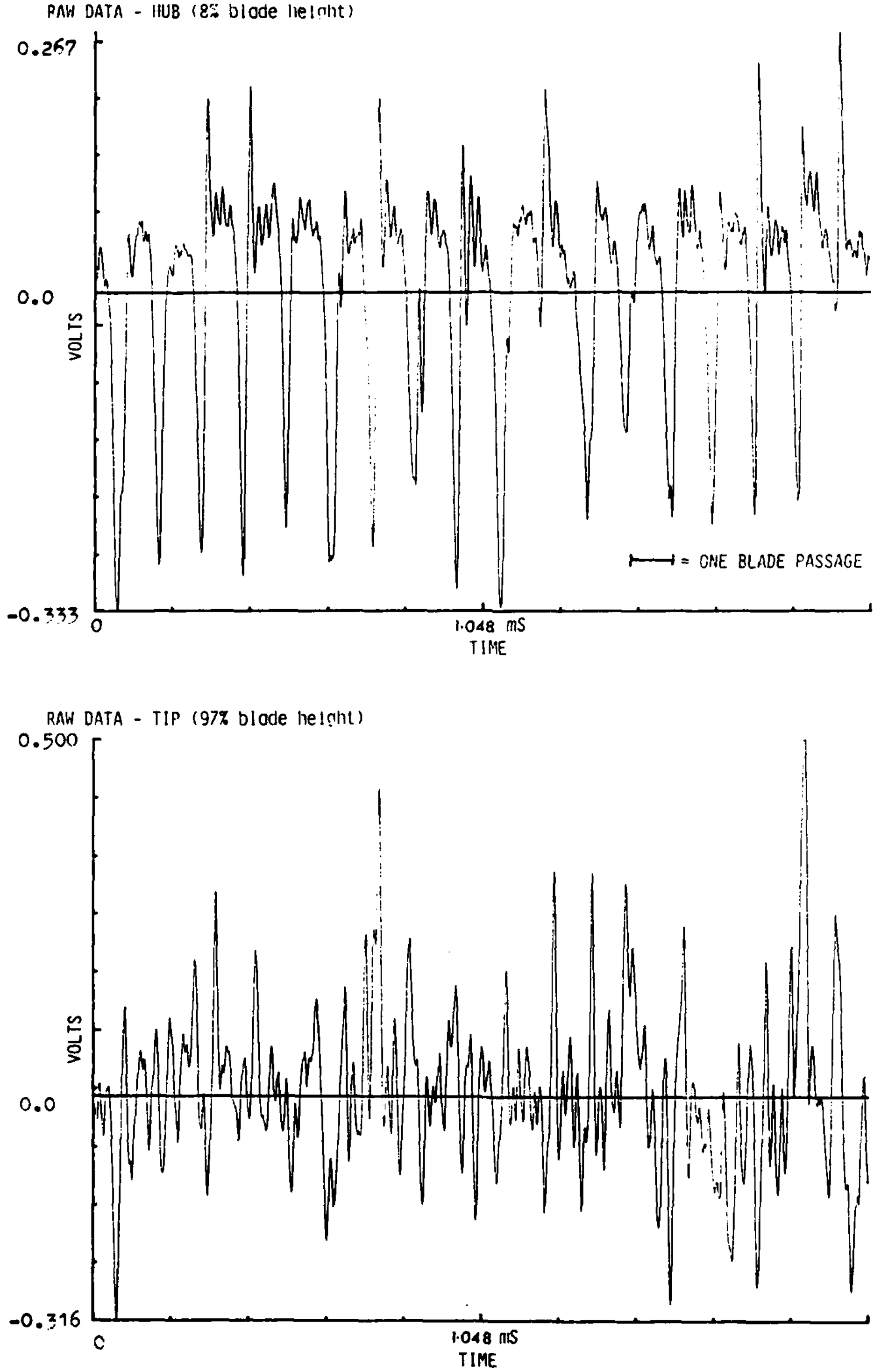

Fig 8 Comparison of raw data at hub and tip - 1st rotor exit

Fig 9

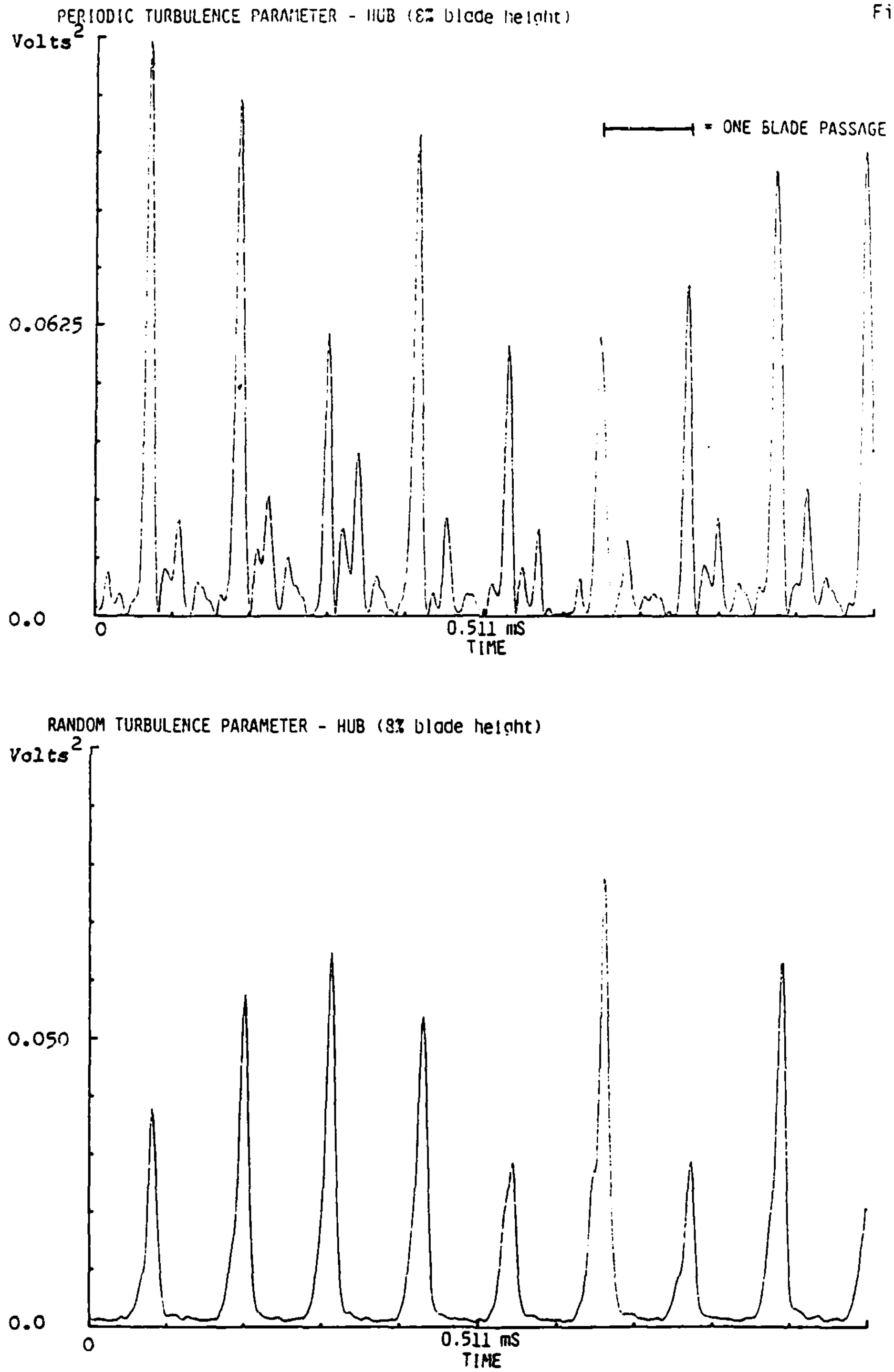

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Fig 9 Periodic and random turbulence parameters at the hub - 1st rotor exit

Fig 10

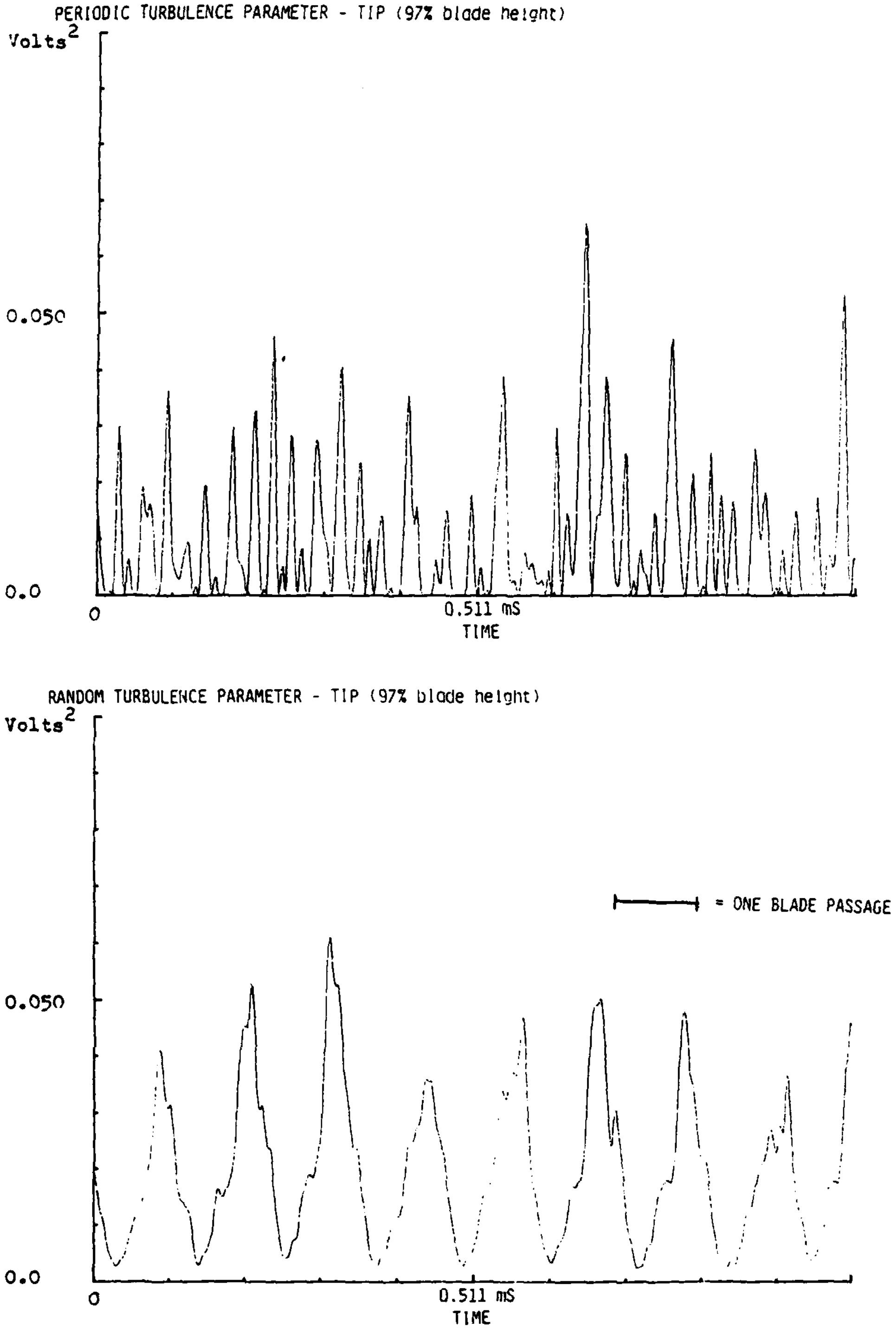

Fig 10 Periodic and random turbulence parameters at the tip - 1st rotor exit

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Fig 11

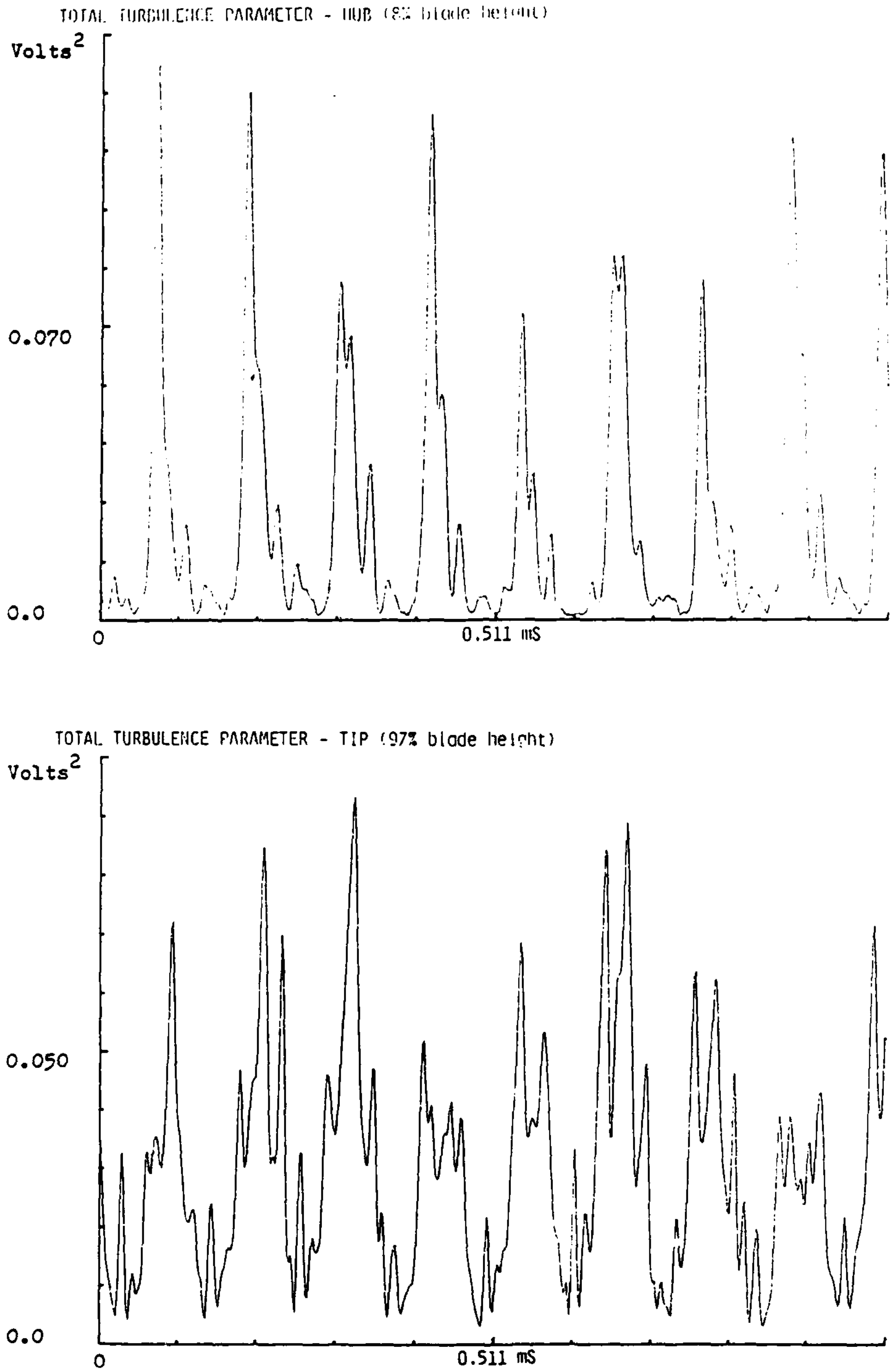

Fig 11 Total turbulence parameters at hub and tip - 1st rotor exit

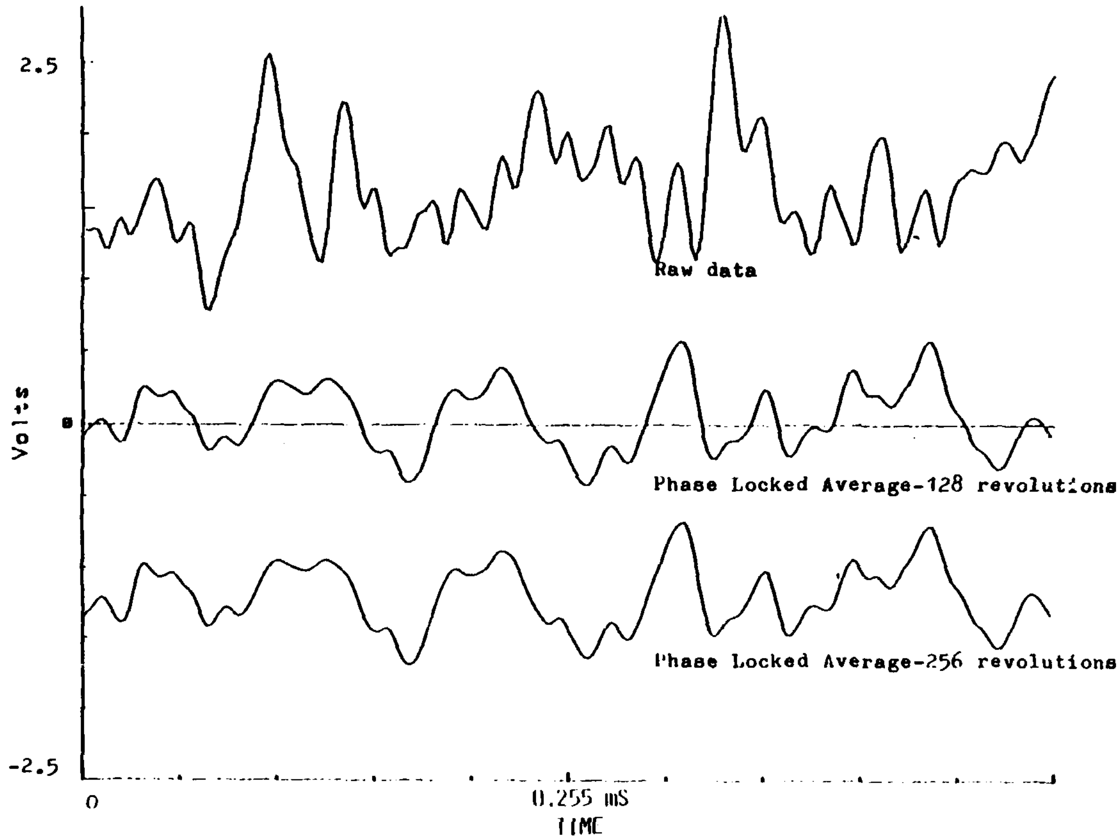

Fig 12 Phase locked average trace over 128 and 256 revs - 3rd rotor exit (98% blade height)

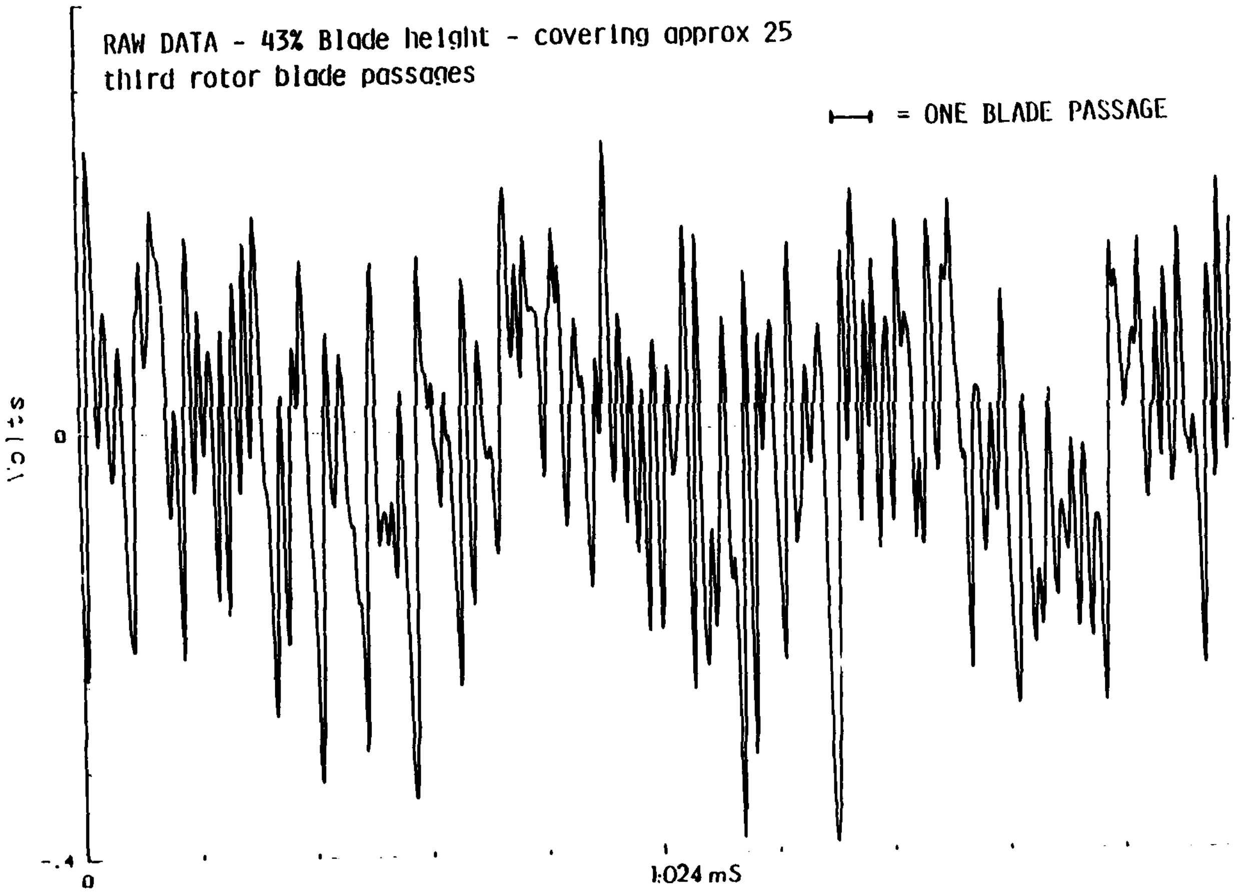

Fig 13 Raw data - mid height 3rd rotor exit

Fig 14

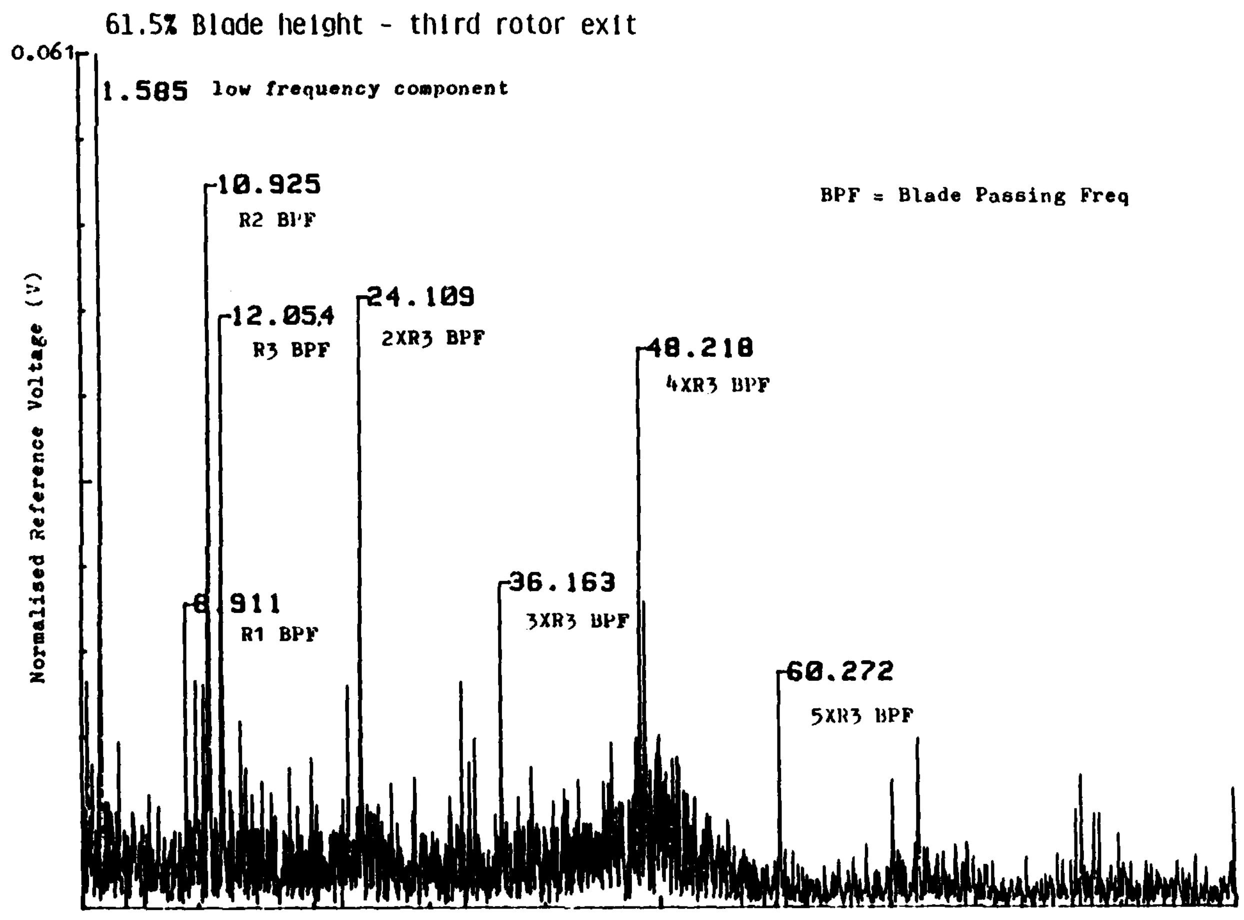

Fig 14 Fast Fourier transform of data shown in Fig 13

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16. Descriptors (Keywords) (Descriptors marked * are selected from TEST)

Turbomachinery*. Axial flow compressors*. Unsteady flow*. Turbulence*. Data acquisition*. Unsteady pressure measurement*. C147

17. Abstract

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